

Enhancing Systems Thinking Through Outdoor Permaculture-Based Science Learning

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ABSTRACT Systems thinking is a key competency for sustainability. It can help students to analyze complex matters easily. This study aims to investigate students' improvement in systems thinking through outdoor permaculture learning. Permaculture is an artificial ecosystem that promotes sustainable agriculture. There are four learning stations within the permaculture, including a mini-garden, an aquaponic system, a composting system, and a black soldier fly farm. This study used a quantitative research method with a nonequivalent (pretest and posttest) control-group design. Students in the control group followed the regular classroom learning. Meanwhile, the students in the experimental group followed the outdoor permaculture learning. The sample included 50 tenth-grade students from a high school in Bandung. Essay questions were used to assess students' systems thinking, with item analysis confirming that the instrument was both valid and reliable. A t-test showed a significant difference in students' improvement in systems thinking between the two groups ($p = 0.01$). The experimental group showed greater improvement in systems thinking competency. In addition, Cohen's d value (0.73) indicated a moderate effect size, reflecting a meaningful difference in the gains of systems thinking competency between the two groups. Based on the data, it can be concluded that outdoor permaculture learning is an effective way to enhance students' systems thinking. This study offers a new perspective on the use of integrated learning stations in a permaculture setting to strengthen students' systems thinking and support sustainable learning practices in schools.

Keywords: Outdoor permaculture learning, Systems thinking, Ecosystem

1. INTRODUCTION

The concept of systems thinking was first introduced by Barry Richmond in 1987 and has since been continuously developed and redefined through various perspectives (Arnold & Wade, 2015). It is now recognized as a key competence for both sustainable development and digital transformation (Armenia et al., 2022). Systems thinking enables individuals to understand the bigger picture, address the root causes of unsustainability rather than surface-level symptoms, and create conditions for sustainability to thrive (Demssie et al., 2023; Voulvoulis et al., 2022). According to UNESCO (2017), systems thinking competency comprises four core abilities: recognizing and understanding relationships; analyzing complex systems; understanding how systems are embedded across different domains and scales; and dealing with uncertainty.

The mastery of systems thinking competency can help students learn in the classroom. It can support better

problem-solving skills (Kourayem & Ghadim, 2021). It enables learners to view phenomena holistically and understand the interrelationships among system components. Furthermore, Johariah et al. (2023) suggested that students with strong systems-thinking competency can easily connect one topic to another, leading to a deeper, more integrated understanding of the subject matter. Numerous studies have examined systems thinking in education. Previous studies examining students' systems-thinking profiles indicate that students still lack systems-thinking competency. For example, Nuraeni et al. (2020) and Baharuddin (2025) reported that most students demonstrated low levels of systems thinking. Similarly, Gilissen et al. (2020) stated that systems thinking has not been effectively integrated into classroom practices.

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Ecosystems were the most frequently addressed domain-specific topic in systems-thinking studies in education (Seher & Defne, 2024). As ecosystems comprise numerous interconnected and complex components, analyzing these systems is crucial for a thorough understanding. This demands strong systems thinking, as learners must recognize interactions, feedback loops, and dynamic relationships within ecological systems. Davis and Stroink (2016) emphasized that systems thinkers are better equipped to identify their own role within a system and grasp the complexities of ecological systems, including their socio-economic influences. Furthermore, Amissah et al. (2020) highlighted systems thinking as a reasoning approach for tackling real-world problems, grounded in the fundamental concept of a "system."

Previous studies have highlighted the relevance of systems thinking in supporting students' understanding of complex phenomena such as ecosystems. For example, systems thinking and modeling approaches have been used to analyze factors affecting ecosystems under conditions of climate change and ecological dynamics (Lankers et al., 2023; Phan et al., 2024). Several studies have recommended instructional strategies such as environmental-based learning, field studies, and the use of real-world phenomena or objects that students can directly observe and analyze (Zidan et al., 2023). In this context, permaculture offers a promising learning environment that supports students' understanding of ecosystems while fostering the development of systems-thinking skills.

Permaculture is a constructed ecosystem designed to meet human needs while promoting sustainability (Alakendu et al., 2024). It is defined as a creative design process based on systems thinking (Althouse, 2016), serving as a holistic framework that integrates sustainable agricultural practices to address the economic, social, and environmental dimensions of sustainability (Didarali & Gambiza, 2019). This aligns with the Sustainable Development Goals, which consider economic, social, and environmental aspects in their implementation (Mensah, 2019). Permaculture-based learning incorporates outdoor activities, providing students with real-world objects and phenomena to observe and analyze. Outdoor activities and real-world objects make the learning process more meaningful and improve learning outcomes, including cognitive skills (Saefudin et al., 2025; Valentini & Donatiello, 2021). Permaculture offers a rich learning environment that serves as a powerful resource for teaching ecosystem concepts. Therefore, outdoor permaculture-based learning offers students opportunities to engage in real-world, hands-on experiences to explore ecological interactions while simultaneously developing their systems-thinking skills.

Numerous studies have focused on improving students' systems-thinking competency, recognizing its importance for a deeper understanding of complex interrelationships

across contexts. However, there is a noticeable gap in the literature regarding the potential of outdoor permaculture-based learning as a strategy to enhance students' systems-thinking competency. Therefore, this study aims to investigate how outdoor permaculture learning improves students' systems-thinking competency. The research questions are as follows:

- To what extent does outdoor permaculture-based science learning enhance students' systems thinking compared to conventional science learning?
- How do specific learning activities at each permaculture learning station facilitate the development of students' systems thinking competency?

2. METHOD

2.1 Research Design

The research method employed in this study was a quasi-experimental design, which does not involve the random assignment of participants to groups (Fraenkel et al., 2023). A quantitative approach was adopted, using a nonequivalent control-group design with both pretest and posttest measures. In this design, two existing classes were assigned as the control and experimental groups. Both groups completed a pretest before the learning intervention to assess their initial level of systems-thinking competency. The experimental group then received the treatment through outdoor permaculture learning, while the control group continued with conventional classroom instruction. After the intervention, both groups completed a posttest. This design enables comparisons of learning gains across groups and the evaluation of the intervention's effectiveness (Creswell, 2014). The research design is shown in Table 1.

Table 1 Nonequivalent (pretest and posttest) control-group design.

Control group	Pretest	No treatment	Posttest
Experimental group	Pretest	Experimental treatment	Posttest

2.2 Participant

The study population consisted of tenth-grade students from a high school in Bandung. The sampling technique employed was convenience sampling, based on participants' accessibility and availability. The final sample included 50 students aged 15-16 years. These students were divided into two existing classes, each with 25 students, as shown in Table 2. One class was assigned to the control group, which used the conventional learning approach. The other class served as the experimental group and participated in the outdoor permaculture learning program, which included learning stations designed to simulate real-world ecosystem interactions. Both groups received instruction on the duplicate content, but through different

Table 2 Participant demography by group

Gender	Group	
	Control	Experimental
Male	12	14
Female	13	11

learning environments, allowing a comparison of their learning outcomes, particularly in terms of systems-thinking competency.

2.3 Instrument

The research instrument used in this study was a test comprising seven essay questions on ecosystem topics. The test instrument was developed based on aspects of systems thinking competency, as outlined by UNESCO (2017). The systems thinking aspects are shown in Table 3.

Table 3 Systems thinking aspects and instrument framework.

Aspect	Indicator
The ability to recognize and understand relationships.	Students demonstrate the ability to apply the concept of ecological interactions to real-life contexts.
To analyse complex systems.	Students can identify the role of each component in an ecosystem. Students demonstrate the ability to analyze the dynamic balance that exists within ecosystems.
To think of how systems are embedded within different domains and different scales.	Students can demonstrate the interconnection among economic, social, and environmental aspects within the context of ecosystems. Students demonstrate the ability to assess the impact of ecosystem changes at both local and global scales.
To deal with uncertainty.	Students can predict the impacts of changes in the components of an ecosystem. Students demonstrate the ability to propose multiple alternative solutions to the issues presented.

The construct validity of the research instrument was assessed through expert judgment to ensure that each item accurately represented the intended constructs. Revisions were made based on their feedback to improve clarity, relevance, and alignment with the study's objectives. The validity and reliability of the instrument were calculated using ANATES 4.0 software. The validity analysis showed that item-total correlations ranged from 0.49 to 0.81, indicating that all items were valid. The reliability coefficient was 0.77, indicating high internal consistency.

2.4 Procedure

This research was conducted in November – December 2024. The initial stage of the research involved a comprehensive literature review of prior studies on systems thinking competency and outdoor permaculture learning, which served as the foundation for the study's design. To

gain insights into existing teaching practices and ensure contextual relevance, observations and semi-structured interviews were conducted with the biology teacher. These activities helped identify the learning needs and opportunities within the school environment.

The preparation stage included developing both research instruments and instructional materials. The instruments consisted of a systems-thinking competency, validated through expert judgment. Instructional materials were designed to align with the curriculum and included lesson plans, student worksheets, learning resources, and a detailed layout of the permaculture learning stations. The permaculture design incorporated four integrated learning stations — gardening, aquaponics, composting, and black soldier fly farming — that provided authentic, real-world learning environments for the experimental group. Figure 1 illustrates the sequential flow of the research procedure, from planning to data collection and analysis.

Both the control and experimental groups took the pretest before the learning session. The students in the control group followed the regular learning process. Meanwhile, the students in the experimental group followed an outdoor permaculture learning program. Each group participated in four learning sessions. Each group explored two different landscapes to observe and learn about ecosystems and their respective components. The control group explored the school area, which included a mini-park and a fish pond. The experimental group explored the permaculture area, which comprises four main areas: a gardening area, an aquaponic area, a composting area, and a black soldier fly (*Hermetia illucens*) area. Both groups took the posttest after they completed all the learning sessions. The students completed their assignments and engaged in group learning activities.

2.5 Data Analysis Techniques

The level of students' systems thinking competency was assessed using the Systems Thinking Competency Assessment Rubric developed by Semiz and Teksöz (2019). The rubric categorizes systems thinking competencies into four levels: pre-aware, emerging, developing, and mastery. Based on the pretest results, no significant difference in students' systems thinking competency was found between the two groups. Therefore, the posttest results from both groups were compared to assess whether outdoor permaculture learning led to a significant improvement in students' systems-thinking competency. The improvement in systems thinking competency for both groups was analyzed using Hake's (1998) N-gain formula. Prior to conducting the analysis, tests for normality (Shapiro-Wilk) and homogeneity of variance (Levene test) were performed. The results indicated that the data met the assumptions for using a parametric test. Therefore, an independent-samples t-test was applied to compare students' learning outcomes in systems thinking competency between the two groups. In addition, Cohen's *d* was calculated to determine the

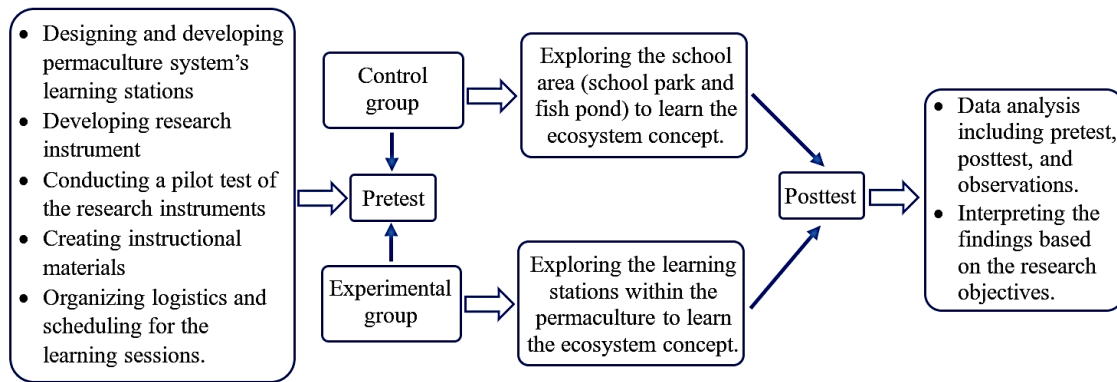


Figure 2 The flow of the research procedure

effect size of the outdoor permaculture learning on improving students' systems thinking competency.

3. RESULT AND DISCUSSION

3.1 Students' Systems Thinking Development

Outdoor permaculture-based learning exposes students to complex real-world systems and enables them to solve ecosystem-related issues through collaboration. The regular learning process focused on teaching students about ecosystems. Table 4 shows the pretest and posttest results from both groups. The experimental group shows slightly greater improvement than the control group. Both groups demonstrated improvement in systems thinking competency, as indicated by the pretest and posttest results. This suggests that both learning approaches can help students develop systems-thinking competency. Based on the posttest t-test results, there was a significant difference in systems thinking competency between the two groups ($p = 0.01$). The experimental group showed greater improvement in systems thinking competency.

The initial level of students' systems-thinking competency, shown in Figure 2, varied across categories. The distribution of students' systems-thinking competency across levels was almost identical between the two groups. Most of the students in both groups were at the developing level. A few students had already reached the mastery level, but most of them were still at the emerging and developing levels. This underscores the need to strengthen systems thinking competencies among the majority of students. Based on the students' test responses, some were unable to

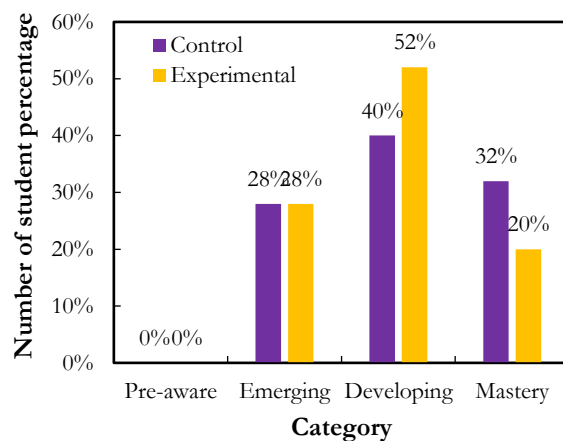


Figure 1 Initial level of students' systems thinking competency

explain the interrelationships among components within a system fully. Although understanding the interrelationships between components is a fundamental aspect of systems thinking, some students have yet to master this concept. This phenomenon has also been identified in elementary students (Mulyadiprana et al., 2024) and pre-service teachers (Semiz & Teksöz, 2019). This indicates that students still require additional support and practice to comprehend the connections between various system components fully.

The posttest data in Figure 3 indicate that students in both the control and experimental groups improved their systems thinking competencies. All students reached either the developing or mastery level, which demonstrates positive learning outcomes. This suggests that learning ecosystem topics, regardless of the learning environment, can enhance students' systems thinking. These findings are consistent with those of Lankers et al. (2023), who reported that students who engaged in modeling ecological systems demonstrated significant gains in systems-thinking competencies. Ecosystem-related content naturally lends itself to systems thinking because it involves analyzing complex, dynamic relationships within and across systems (Martín-Gómez et al., 2018).

Table 4 Comparison of students' systems-thinking competency between the pretest and posttest.

Data Comparison	Control		Experimental	
Number of students	25		25	
Data type	Pretest	Posttest	Pretest	Posttest
Mean	63.25	78.58	61.50	83.92
Standard deviation	14.06	7.21	12.37	7.35
Lowest score	39.58	62.50	41.67	72.92
Highest score	81.25	91.67	83.34	95.83

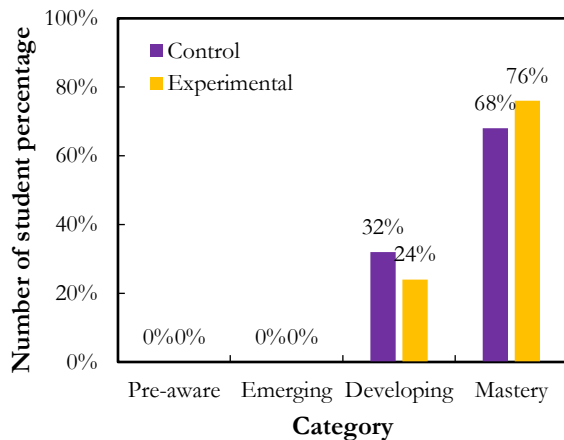


Figure 4 Level of students' systems thinking competency after completing all learning sessions

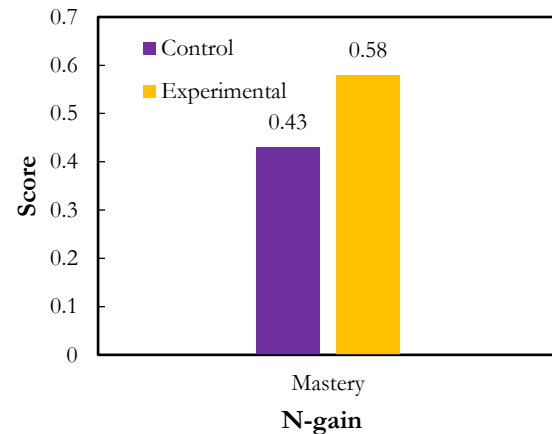


Figure 3 Comparison of N-gain scores between the two groups

The N-gain scores of both groups indicate a more profound understanding that each learning approach has a distinct influence. Figure 4 shows the comparison of the N-gain percentage level between the control and experimental groups. The N-gain scores of both groups fell within the same category, indicating a moderate level. However, the experimental group showed a slightly higher average score than the control group. This suggests that while both learning approaches were practical to a moderate extent, outdoor permaculture learning had a greater impact on improving students' systems-thinking competency. In addition, based on Cohen's *d* of 0.73, the intervention's effect size was considered moderate, indicating a meaningful difference in systems thinking competency between the two groups.

A key part of the learning process in this study involved identifying and analyzing the interconnections between components in an ecosystem. Understanding such relationships is a fundamental aspect of systems thinking. According to Behl and Ferreira (2014), recognizing the interactions among system elements is a key factor in the development of systems thinking. Similarly, Arnold and Wade (2015) emphasized that the ability to perceive and interpret relationships between system components is a fundamental principle of systems thinking. Therefore, the improvement in students' competencies can be attributed to learning experiences that encouraged them to think holistically and engage with the complexity of ecological systems.

3.2 The Role of Permaculture Learning Stations in Facilitating Systems Thinking

The permaculture used in this study was established within an existing greenhouse, with several new additions to support the students' learning. The primary focus of the permaculture development is on ecosystem concepts and the core values of permaculture. Krebs and Bach (2018) stated that permaculture design principles, along with a framework for ecosystem mimicry and complex-system

optimization, constitute the significant differences from other alternative agricultural approaches. The four main learning stations in this permaculture study are the mini-garden, the aquaponic installation, the composting site, and the black soldier fly farm station. All learning stations are designed to facilitate students' observation and exploration of the components within each station. The learning stations applied sustainability values and emphasized fulfilling human needs while considering economic, social, and environmental aspects.

The first learning station in the permaculture system is the mini-garden, a key component of the overall educational experience. One notable feature of the mini-garden is the intentional avoidance of agricultural pest control methods that rely on chemical substances. This decision enables natural interactions among biotic components—such as plants, insects, and microorganisms—to unfold in accordance with the principles of a healthy, functioning ecosystem. Numerous studies have highlighted the adverse effects of chemical pest control, particularly the use of pesticides, on the environment and human health. The use of chemicals in agriculture has raised significant concerns about its long-term impact on ecosystems (Omran & Negm, 2020; Tudi et al., 2021) and human health (Pathak et al., 2022).

The mini-garden learning station aims to help students identify the components of a garden ecosystem—producers, consumers, and decomposers—and understand their interactions. Its rich biodiversity enables observation of natural pest control mechanisms, such as predator-prey relationships and biological diversity. Students engage in identifying biotic and abiotic components, constructing food chains, and analyzing the role of each element, which supports the development of systems thinking, particularly the ability to recognize and understand relationships (Vachliotis et al., 2021). This experiential approach fosters deeper ecological understanding and systems analysis. Compared to the

limited biodiversity in the schoolyard, the permaculture setting offers a richer context. However, students in the control group were still able to construct basic food chains.

The aquaponic learning station serves as a practical demonstration of biogeochemical cycles, particularly the nitrogen cycle, which is a key process in aquatic environments (Krastanova et al., 2022; Wongkiew et al., 2017). An aquaponic system effectively illustrates nitrogen cycling within an ecosystem by combining fish farming with hydroponic plant growth, creating a symbiotic relationship in which fish waste provides nutrients for the plants, and the plants filter and purify the water for the fish (Rains & Whitworth, 2018). In contrast, students in the control group learned about the biogeochemical cycle more abstractly, through textbooks and simple animated videos, which may have limited their understanding of the cycle's real-world applications. The aquaponic installation, however, offers students a tangible, real-world example that significantly deepens their understanding of these complex biological processes. This aligns with the findings of Suyanto et al. (2022), who stated that learning through real-world objects and experiences helps students reach their full potential in acquiring factual knowledge and in connecting theory and practice.

The biogeochemical cycle, particularly the nitrogen cycle, is a complex system involving numerous interconnected components, both biotic and abiotic (Aprilia et al., 2022; Ma et al., 2021). By engaging with the aquaponic system, students can better analyze and understand the relationships among its components, thereby strengthening their systems-thinking skills. Junge et al. (2017) suggest that aquaponics can be both an enjoyable and effective way to learn environmental science, as it combines practical knowledge with environmental awareness. Furthermore, Mambrey et al. (2022) found that students' systems thinking evolves from simple cause-and-effect reasoning to more sophisticated thinking by incorporating a greater number of variables and relationships. The findings of this study support this idea, as students in the experimental group who learned through the aquaponic system demonstrated significant improvements in their systems thinking competency, illustrating the effectiveness of experiential learning in complex systems.

The composting site is the third learning station in the outdoor permaculture learning. This station focuses on the management and utilization of organic waste. This learning station emphasizes sustainable practices in organic waste management. In addition, students can observe and analyze the composting process. Several factors influence composting, including the materials used, reactors, temperature, and microorganisms (Yin et al., 2024). In this learning station, students are introduced to the three pillars of sustainability: economic, social, and environmental. Recognizing these three foundational aspects of

sustainability is considered a key competency in systems thinking (Purvis et al., 2019; UNESCO, 2017). Therefore, the composting station can effectively help students understand the pillars of sustainability, which are a crucial component of systems thinking competency.

The black soldier fly farm learning station also demonstrates the three pillars of sustainability by offering an economically viable solution for organic waste management that can generate revenue from the sale of larvae and byproducts. Detritivores, such as black soldier fly larvae, provide a sustainable solution for protein production, waste management, and the promotion of a circular bioeconomy (Kurnia et al., 2018; Odongo et al., 2024). Additionally, at this learning station, students are introduced to the concept of sustainability, encompassing both local and global scales. Unlike conventional classroom-based instruction, outdoor learning allows students to engage actively with real-world ecological systems, fostering deeper connections with the material (Mann et al., 2022). While students in the control group also participated in hands-on activities, the intensity and depth of their involvement did not match that of the experimental group, which engaged more directly with the natural environment. This difference in students' involvement in the learning process highlights the added value of outdoor learning, which is often cited as a more effective approach for enhancing student engagement and understanding (Ayotte-Beaudet et al., 2023).

4. CONCLUSION

Outdoor permaculture learning has a significant positive impact on students' systems thinking competency. Each learning station within the permaculture system contributes to students' development of critical thinking skills regarding complex systems and their interrelated components. Based on the findings of this study, it can be concluded that outdoor permaculture learning is notably effective in improving students' systems thinking competency. The integration of permaculture practices into the learning process not only deepens students' understanding of ecosystem concepts but also enhances their ability to apply this knowledge in real-world contexts.

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REFERENCES

Alakendu, P. R., Afiya, R. S., Senthilkumar, S., & Manivannan, S. (2024). Permaculture : A Sustainable Farming Approach for the Modern

- Era. *Haya: The Saudi Journal of Life Sciences*, 9(7), 305–312. <https://doi.org/10.36348/sjls.2024.v09i07.009>
- Althouse, K. (2016). *An Instructional Module on Permaculture Design Theory for Landscape Architecture Students* [Utah State University]. <https://digitalcommons.usu.edu/gradreports/793>
- Amissah, M., Gannon, T., & Monat, J. (2020). What is Systems Thinking? Expert Perspectives from the WPI Systems Thinking Colloquium of 2 October 2019. *Systems*, 8(1), 6. <https://doi.org/10.3390/systems8010006>
- Aprilia, D., Dianti, Kirana, N. A., Agustina, P. C., Lia, K., Sarnp, Khairul, A. B. A. R., & Ahmad, D. S. (2022). Review: Biogeochemical Process in Mangrove Ecosystem. *International Journal of Bonorowo Wetlands*, 10(2), 126–141. <https://doi.org/10.13057/bonorowo/w100205>
- Armenia, S., Tsaples, G., Papathanasiou, J., Barnabé, F., & Nazir, S. (2022). Systems Thinking as A Key Competence for Sustainable Development and Digital Transformation. *ICERI2022 Proceedings*, 1, 2006–2011. <https://doi.org/10.21125/iceri.2022.0506>
- Arnold, R. D., & Wade, J. P. (2015). A Definition of Systems Thinking: A Systems Approach. *Conference on Systems Engineering Research*, 44, 669–678. <https://doi.org/10.1016/j.procs.2015.03.050>
- Ayotte-Beaudet, J. P., Chastenay, P., Beaudry, M. C., L'Heureux, K., Giamellaro, M., Smith, J., Desjarlais, E., & Paquette, A. (2023). Exploring the Impacts of Contextualised Outdoor Science Education on Learning: The Case of Primary School Students Learning about Ecosystem Relationships. *Journal of Biological Education*, 57(2), 277–294. <https://doi.org/10.1080/00219266.2021.1909634>
- Baharuddin, R. (2025, April). Analysis of students' systems-thinking competency profile on ecosystem issues. In *Proceedings International Conference of Sustainable Innovation* (Vol. 1, pp. 190-194).
- Behl, D. V., & Ferreira, S. (2014). Systems Thinking: An Analysis of Key Factors and Relationships. *Procedia Computer Science*, 36, 104–109. <https://doi.org/10.1016/j.procs.2014.09.045>
- Creswell, J. W. (2014). *Research design: qualitative, quantitative, and mixed methods approaches* (Vol. 54). United States of America: Sage Publications.
- Davis, A. C., & Stroink, M. L. (2016). The Relationship between Systems Thinking and the New Ecological Paradigm. *Systems Research and Behavioral Science*, 33(4), 575–586. <https://doi.org/https://doi.org/10.1002/sres.2371>
- Demssie, Y. N., Biemans, H. J. A., & Wesselink, R. (2023). Fostering Students' Systems Thinking Competence for Sustainability by Using Multiple Real-World Learning Approaches. *Environmental Education Research*, 29(2), 261–286. <https://doi.org/10.1080/13504622.2022.2141692>
- Didarali, Z., & Gambiza, J. (2019). Permaculture: Challenges and Benefits in Improving Rural Livelihoods in South Africa and Zimbabwe. *Sustainability*, 11(8), 2219. <https://doi.org/10.3390/su11082219>
- Fraenkel, J. R., Wallen, N., & Helen, H. H. (2023). How to Design and Evaluate Research in Education. In *McGraw-Hill Higher Education (Eleventh Ed.)*. McGraw-Hill Education.
- Gilissen, M. G. R., Knippels, M. C. P. J., & van Joolingen, W. R. (2020). Bringing Systems Thinking into the Classroom. *International Journal of Science Education*, 42(8), 1253–1280. <https://doi.org/10.1080/09500693.2020.1755741>
- Hake, R. R. (1998). Interactive-Engagement Versus Traditional Methods: A Six-Thousand-Student Survey of Mechanics Test Data for Introductory Physics Courses. *American Journal of Physics*, 66(1), 64–74. <https://doi.org/10.1119/1.18809>
- Johariah, J., Jalmo, T., & Lengkana, D. (2023). Pengembangan Instrumen Penilaian Untuk Mengukur Kemampuan Berpikir Sistem Siswa SMP Pada Materi Pencemaran Lingkungan [Development of an Assessment Instrument to Measure Junior High School Students' Systems Thinking Skills on Environmental Pollution Material]. *JUPE : Jurnal Pendidikan Mandala*, 8(1), 527. <https://doi.org/10.58258/jupe.v8i1.5501>
- Junge, R., König, B., Villarroel, M., Komives, T., & Jijakli, M. H. (2017). Strategic Points in Aquaponics. *Water (Switzerland)*, 9(3), 1–9. <https://doi.org/10.3390/w9030182>
- Kourayem, F. T., & Ghadim, M. K. (2021). A Review of System Thinking and Wise Organization. *New Applied Studies in Management, Economics & Accounting*, 4(3), 7–23. <https://doi.org/10.22034/nasmea.2021.176216>
- Krastanova, M., Sirakov, I., Ivanova-Kirilova, S., Yarkov, D., & Orozova, P. (2022). Aquaponic Systems: Biological and Technological Parameters. *Biotechnology & Biotechnological Equipment*, 36(1), 305–316. <https://doi.org/10.1080/13102818.2022.2074892>
- Krebs, J., & Bach, S. (2018). Permaculture — Scientific Evidence of Principles for the Agroecological Design of Farming Systems. *Sustainability*, 10(3218), 1–24. <https://doi.org/10.3390/su10093218>
- Kurnia, N., Baharuddin, R., Ngitung, R., & Auliah, A. (2018). Lalat Hijau *Lucilia sericata* sebagai Agen Biokonversi Sampah Organik: Pengamatan Siklus Hidup [Green Fly *Lucilia sericata* as an Agent for Bioconversion of Organic Waste: Observation of its Life Cycle].
- Lankers, A., Timm, J., & Schmiemann, P. (2023). Students' Systems Thinking while Modeling a Dynamic Ecological System. *Frontiers in Education*, 8(7), 1–14. <https://doi.org/10.3389/educ.2023.1187237>
- Ma, B., Stirling, E., Liu, Y., Zhao, K., Zhou, J., Singh, B. K., Tang, C., Dahlgren, R. A., & Xu, J. (2021). Soil Biogeochemical Cycle Couplings Inferred from a Function-Taxon Network. *Research: A Science Paper Journal*, 2021, 1–10. <https://doi.org/10.34133/2021/7102769>
- Mambrey, S., Schreiber, N., & Philipp, S. (2022). Young Students' Reasoning About Ecosystems: The Role of Systems Thinking, Knowledge, Conceptions, and Representation. *Research in Science Education*, 52, 79–98. <https://doi.org/10.1007/s11165-020-09917-x>
- Mann, J., Gray, T., Truong, S., Brymer, E., Passy, R., Ho, S., Sahlberg, P., Ward, K., Bentsen, P., Curry, C., & Cowper, R. (2022). Getting Out of the Classroom and Into Nature: A Systematic Review of Nature-Specific Outdoor Learning on School Children's Learning and Development. *Frontiers in Public Health*, 10(May). <https://doi.org/10.3389/fpubh.2022.877058>
- Martin-Gámez, C., Acebal, M. del C., & Prieto, T. (2018). Developing The Concept of 'Ecosystem' Through Inquiry-Based Learning: A Study of Pre-Service Primary Teachers. *Journal of Biological Education*, 54(2), 147–161. <https://doi.org/10.1080/00219266.2018.1554596>
- Mensah, J. (2019). Sustainable Development: Meaning, History, Principles, Pillars, and Implications for Human Action: Literature Review. *Cogent Social Sciences*, 5(1), 1–21. <https://doi.org/10.1080/23311886.2019.1653531>
- Mulyadiprana, A., Hamdu, G., & Ade, Y. (2024). STEL (System Thinking and ESD Learning) Model: Developing Elementary School Students' Systems Thinking Skills. *Jurnal Kependidikan: Jurnal Hasil Penelitian Dan Kajian Kepustakaan Di Bidang Pendidikan, Pengajaran Dan Pembelajaran*, 10(4), 1665–1674. <https://doi.org/10.33394/jk.v10i4.12861>
- Nuraeni, R., Setiono, & Himatul, A. (2020). Profil Kemampuan Berpikir Sistem Siswa Kelas XI SMA pada Materi Sistem Pernapasan [Profile of Systems Thinking Ability of Grade XI High School Students on Respiratory System Material]. *Pedagogi Hayati*, 4(1), 1–9. <https://doi.org/10.31629/ph.v4i1.2123>
- Odongo, E. E., Bbosa, W. K., & Kahunde, P. K. (2024). Black Soldier Fly (BSF): A Sustainable Solution for Protein, Waste Management, and a Circular Bio-Economy. *European Journal of Theoretical and Applied Sciences*, 2(3), 822–834. [https://doi.org/10.59324/ejtas.2024.2\(3\).64](https://doi.org/10.59324/ejtas.2024.2(3).64)
- Omran, E. S. E., & Negm, A. (2020). Impacts of pesticides on soil and water resources in Algeria. In *Water resources in Algeria-Part I: assessment of surface and groundwater resources* (pp. 69–91). Cham: Springer International Publishing.

- Pathak, V. M., Verma, V. K., Rawat, B. S., Kaur, B., Babu, N., Sharma, A., Dewali, S., Yadav, M., Kumari, R., Singh, S., Mohapatra, A., Pandey, V., Rana, N., & Cunill, J. M. (2022). Current Status of Pesticide Effects on Environment, Human Health, and Its Eco-Friendly Management as Bioremediation: A Comprehensive Review. *Frontiers in Microbiology*, *13*(August), 1–29. <https://doi.org/10.3389/fmicb.2022.962619>
- Phan, T., Bertone, E., Neelamraju, C., Nguyen, N., & Quyet, T. (2024). A Systems Thinking Approach to Understand the Impacts of Pesticides on the Great Barrier Reef Ecosystems Under Climate Change. In *Preprint* (Vol. 11, Issue Cicc, pp. 76–84). <https://doi.org/10.2139/ssrn.4683765>
- Purvis, B., Mao, Y., & Robinson, D. (2019). Three Pillars of Sustainability: in Search of Conceptual Origins. *Sustainability Science*, *14*(3), 681–695. <https://doi.org/10.1007/s11625-018-0627-5>
- Rains, S., & Whitworth, B. A. (2018). Building an Aquaponics System in the Classroom. In *Better Way of Farming* (pp. 41–45). Tiger Prints. https://tigerprints.clemson.edu/teach_learn_pub
- Saefudin, K., Suwandi, T., Najira, B., R., & Rachman, H. T. (2025). Integration of Permaculture to Reinvent Students' Interest in Nature and Environmental Awareness for Quality Education Under SDG-4. *Jurnal Pendidikan IPA Indonesia*, *14*(1), 192–201. <https://doi.org/10.15294/jpii.v14i1.22122>
- Seher, B. U., & Defne, C. G. (2024). Research Trends on Systems Thinking Approach in Science Education. *International Journal of Science Education*, *46*(5), 485–502. <https://doi.org/10.1080/09500693.2023.2245106>
- Semiz, G. K., & Teksöz, G. (2019). Developing the Systems Thinking Skills of Pre-Service Science Teachers through an Outdoor ESD Course. *Journal of Adventure Education and Outdoor Learning*, *20*(4), 337–356. <https://doi.org/10.1080/14729679.2019.1686038>
- Suyanto, S., Suratsih, S., Aprilisa, E., & Limiansi, K. (2022). Learning Biology Using Real Objects, ICT, and Blended Learning to Improve Factual and Conceptual Knowledge. *Jurnal Pendidikan IPA Indonesia*, *11*(2), 322–332. <https://doi.org/10.15294/jpii.v11i2.33706>
- Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., Chu, C., & Phung, D. T. (2021). Agriculture Development, Pesticide Application, and Its Impact on the Environment. *International Journal of Environmental Research and Public Health*, *18*(3), 1112. <https://doi.org/10.3390/ijerph18031112>
- UNESCO. (2017). *Education for Sustainable Development Goals*. United Nations Educational, Scientific, and Cultural Organization.
- Vachliotis, T., Salta, K., & Tzougraki, C. (2021). Developing Basic Systems Thinking Skills for Deeper Understanding of Chemistry Concepts in High School Students. *Thinking Skills and Creativity*, *41*(May), 100881. <https://doi.org/10.1016/j.tsc.2021.100881>
- Valentini, M., & Donatiello, P. (2021). Outdoor Education as a Way of Life. *Journal of Physical Education and Sport*, *21*(1), 618–623. <https://doi.org/10.7752/jpes.2021.s1072>
- Voulvoulis, N., Giakoumis, T., Hunt, C., Kioupi, V., Petrou, N., Souliotis, I., Vaghela, C., & Binti Wan Rosely, W. (2022). Systems Thinking as a Paradigm Shift for Sustainability Transformation. *Global Environmental Change*, *75*(May), 102544. <https://doi.org/10.1016/j.gloenvcha.2022.102544>
- Wongkiew, S., Hu, Z., Chandran, K., Lee, J. W., & Khanal, S. K. (2017). Nitrogen Transformations in Aquaponic Systems: A Review. *Aquacultural Engineering*, *76*, 9–19. <https://doi.org/10.1016/j.aquaeng.2017.01.004>
- Yin, J., Xie, M., Yu, X., Feng, H., Wang, M., Zhang, Y., & Chen, T. (2024). A Review of The Definition, Influencing Factors, and Mechanisms of Rapid Composting of Organic Waste. *Environmental Pollution*, *342*, 123125. <https://doi.org/10.1016/j.envpol.2023.123125>
- Zidan, Z., Maftuhah, M., Yusti, D., Rahmat, A. A. R., Riandi, R., & Kusnadi, K. (2023). Learning Strategies on Ecosystem Concepts and Environmental Change: A Pedagogical Study Analysis.